Energy Research and Development Division
FINAL PROJECT REPORT

LOW-COST SENSORS FOR NATURAL GAS PIPELINE MONITORING AND INSPECTION

Prepared for: California Energy Commission
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University of California, Berkeley

JANUARY 2015
CEC-500-2014-104

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Contract Number: 500-10-044

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ACKNOWLEDGEMENTS

We would like to thank our Project Advisory Committee for their support and guidance on this project, especially Mike Bermel and Jimmie Cho of Sempra Energy, Scott Flake and Ross Gould of Sacramento Municipal Utility District, Sunil Shori of the California Public Utility Commission, Francois Rongere and Ben Wu of Pacific Gas & Electric, and James Marean of the Gas Technology Institute. We would also like to thank Avtar Bining, Johann Karkheck, Fernando Pina, Jamie Patterson and Mike Gravely for stimulating discussion and guidance.

This report was written based on contributions from several authors.

PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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Low-cost Sensors for Natural Gas Pipeline Monitoring and Inspection is the final report for the Natural Gas Pipeline Sensors project (contract number 500-10-044) conducted by The Regents of the University of California. The information from this project contributes to Energy Research and Development Division's Energy Systems Integration Program.

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ABSTRACT

The safety and security of the natural gas pipeline system require real-time data from sensors. However, commercially available sensors are expensive, resulting in a need to develop low-cost, low-power sensors that can provide operators real-time data on temperature, pressure, and flow to ensure the safety and integrity of natural gas pipelines.

The research team at University of California (UC), Berkeley determined that the most feasible sensors to make are pressure, flow, and vibration sensors and designed two novel sensors. The team modeled both sensors with a simulation tool, with results that showed potential for appropriate sensitivity and accuracy. The team also designed a sensor package with a radio and battery, and successfully tested this in the laboratory. The research team explored and tested Laser Ultrasound Testing to diagnose structural defects in pipes (such as poor welds), and concluded that this was a viable approach for diagnosing pipelines when they are out of service. Since finding a field-testing site was proving problematic, the research team designed and fabricated a test bed; the test bed was validated by many tests used on gas pipelines, such as X-rays and hydro testing. The research team fabricated the Micro-Electro-Mechanical Systems pressure sensor, flow sensor, and successfully tested the sensors in a laboratory setting. The team then tested the pressure sensor in the test bed, found poor sensitivity, and modified the sensor; the research team found the modified sensor showed good sensitivity and accuracy up to 200 pounds per square inch pressure. The researchers concluded that Micro-Electro-Mechanical Systems sensors could successfully provide operators increased real-time information on pipelines in California to ensure that the pipeline infrastructure can safely and reliably deliver and store supplies.

Keywords: Natural gas pipeline, diagnostics, MEMS sensors, pressure sensor, flow sensor

Please use the following citation for this report:

Nguyen, Son Duy, Pit Pillatsch, Sean Wihera, Paul Wright, Richard M. White, Jim Evans, Igor Paprotny, Therese Peffer, Gaymond Yee. (University of California, Berkeley). 2015. ***Low-cost Sensors for Natural Gas Pipeline Monitoring and Inspection.*** California Energy Commission. Publication number: CEC-500-2014-104.

TABLE OF CONTENTS

LIST OF FIGURES

EXECUTIVE SUMMARY

Introduction

California's natural gas supply is moved through a robust system of above ground and underground pipelines throughout the state. The safety and security of this natural gas system are important priorities for California, especially to prevent catastrophes that result in death, injury, or destruction of property. In addition, natural gas leakage contributes to greenhouse gas emissions; methane has 25 times more global warming potential than carbon dioxide.

This document is the final report of the Natural Gas Pipeline Sensor project, a research project conducted by the University of California (UC), Berkeley to design and test miniature low-cost sensors to improve natural gas pipeline integrity. To ensure safety and integrity, natural gas pipelines are routinely inspected for corrosion and defects using various techniques. These techniques are costly and typically require service interruptions. There exists a need to develop low-cost, low-power sensors that can deliver real-time pressure and flow data.

Project Purpose

This project developed prototype sensors that could provide the most appropriate real-time data to the natural gas pipeline operators to improve pipeline safety and integrity with the least disruption to service. Feasible sensors to prototype were selected and then tested in a laboratory setting and in a test bed site, since field-testing was not feasible.

Project Process and Results

Low-cost semiconductor or "chip" fabrication techniques, such as Micro-Electro-Mechanical Systems can be applied to sensor manufacturing. The researchers investigated the design, fabrication, lab testing and field-testing of pressure, flow, and vibration sensors for gas pipelines.

The research team designed a set of benchmarking metrics: disruption of service, frequency of data reporting, cost, and size and used these metrics to benchmark hydrostatic testing, in-pipe devices, pipe wall diagnostic techniques, and existing sensors. Most diagnostic techniques were intermittent in data reporting or required offline operation, which demands costly service disruption and most off-the-shelf sensors were expensive.

Next, the team developed a sensor package for data transmission, with a battery and low-power radio. For the vibration sensors, off-the-shelf accelerometers are available, and this design was not pursued. The Micro-Electro-Mechanical Systems sensors were tested in the laboratory and successfully showed the accurate transmission of data, with low data loss. Initial estimates show that Micro-Electro-Mechanical Systems sensors can be fabricated for less than $18. Finally, the project team investigated Laser Ultrasonic Testing and concluded that this was a viable approach for diagnosing pipelines when out of service; the prototype micro ultrasonic sensors could measure flow for small diameter pipes (up to 30 inches) and may work in pairs for larger diameter pipes.

Researchers designed, fabricated, and installed a test bed at UC Berkeley to assess the Micro-Electro-Mechanical Systems sensors. The analyzed results included sensitivity, accuracy, and reliability issues. The initial test results of the pressure sensors revealed low sensitivity and additional testing of the modified pressure sensors showed appropriate sensitivity and accurate measure of pressure. The initial tests of the flow sensors, however, found that particles from the interior of the test bed disrupted the measurement.

The team refined the sensors designs for optimum production, resilience in the field (especially erosion and temperature), and explored low-cost insertion techniques. They concluded that the 5 millimeter by 5 millimeter dimensions of each sensor could only be reduced by a significant effort in fabrication and was compatible in field sites. The researchers performed aggressive erosion testing using sandblasting equipment; the Silicon Carbide coating on the flow sensor dramatically reduced erosion damage. The flow sensor was tested at temperatures and the output differed by less than 0.5 percent reflecting superior stability.

Project Benefits

The researchers found that Micro-Electro-Mechanical Systems sensors could successfully provide operators increased real-time information on pipelines in California to ensure that the pipeline infrastructure can safely and reliably deliver and store supplies. This project will benefit California citizens by improving the safety of natural gas pipelines and reduce greenhouse gases. The Natural Gas Sector will also benefit from these proposed sensors, as they will provide immediate notice of any damage that occurs to the pipelines and provide more accurate and efficient diagnosis, and routine maintenance.

At the size of a pencil eraser, the Micro-Electro-Mechanical Systems technology is substantially smaller than existing sensors, which allows simple insertion into the pipelines, potentially while still in service. The sensors may have other applications, such as detecting methane leaks or measuring water flow. According to the Electronic Engineering Times (Johnson, 2013), the Micro-Electro-Mechanical Systems market will top $22 billion by 2018, nearly doubling in value in five years. Intel and Texas Instruments, who are interested in communicating wireless sensors for infrastructures, have contacted the research team regarding business opportunities with these sensors.

Although no direct energy savings are anticipated, the sensors could potentially reduce gas leaks. The low cost (less than $18 each) represents a substantial reduction in sensor costs, and allows a widespread deployment to provide ever-present sensor data such as real-time changes in pressure or flow of natural gas. The sensors could also reduce operational and maintenance costs, especially by reducing offline time.

Finally, these sensors can detect gas leaks, reducing greenhouse gas emissions, as required by Assembly Bill 32 (AB32) and can also help prevent catastrophic events such as explosions due to pipe weld failures.

CHAPTER 1: Introduction

1.1 Problem Statement

California's natural gas supply is conveyed through a robust system of pipelines that run throughout the state, including underneath areas of high population. The safety and security of the natural gas system are important priorities for California, especially the prevention of catastrophic events on the natural gas pipeline that result in death, injury, or destruction of property. In addition, natural gas leakage contributes to greenhouse gas emissions; methane has 25 times more global warming potential than carbon dioxide (Environmental Protection Agency [EPA] 2014). Operators rely on a number of different methods and techniques to manage the integrity of the natural gas pipeline system, to detect threats due to corrosion, cracking, damage by force, and human error (Marean, Hammerschmidt, Adamo, Mensinger, 2013). Electronic leak detection systems include computation pipeline monitoring that uses flow, pressure, temperature and density to determine the operating condition of the pipeline; these are compared to a model to flag unusual events, such as over-pressure or leak (Intel 2014). However, sensors are expensive and the data are often difficult to obtain, resulting in a need to develop low-cost, low-power sensors that can provide operators real-time data on temperature, pressure, and flow to ensure the safety and integrity of natural gas pipelines.

1.2 Project Goals

The goals of this project were to explore micro-electro-mechanical system (MEMS) sensors as a low-cost solution to provide real-time data to ensure pipeline integrity. By using microfabrication techniques, one can now make small but complex and inexpensive sensors to measure many variables relevant for gas pipelines, such as instantaneous gas pressure, gas flow velocity, humidity inside the pipe, and vibration of the pipe. An example of a micro fabricated sensor is the ubiquitous accelerometer used in vehicles that sets off the airbags in case of a collision. These small devices cost only a few dollars, they require little electric power, and they are able to determine when an acceleration or deceleration is large enough to warrant outputting a triggering alarm. These accelerometers and a number of the devices discussed in this report are often referred to as MEMS devices.

1.3 Project Objectives

The objective of this project is the design, fabrication, lab testing, and field-testing of next generation low-cost sensor packages for use in gas pipelines, namely flow, pressure, and vibration sensor. First, the research team would determine what kinds of low-cost miniature sensors could be used to provide real-time data to the natural gas pipeline operators. Then the team would design and prototype the sensors, test them in laboratory setting, and test in the field if possible (but if not, test in alternative site that emulates the field conditions.) In the end, field-testing was not possible, and the research team fabricated an inert vessel to emulate field conditions.

CHAPTER 2: Benchmark Existing Diagnostic Approaches

The team solicited assistance from local gas companies to develop benchmarking metrics and then benchmarked existing equipment against those metrics.The goal was to benchmark existing diagnostic approaches to measuring pressure, detecting welding defects, and detecting water accumulation and corrosion in natural gas pipelines. The research team used commercial off-the-shelf products for the benchmarking. The same metrics were used to benchmark new sensors being developed by this project. The full Benchmarking report may be found in Appendix A.

2.1 Benchmarking Metrics

The research team engaged with three investor-owned utilities in California (Pacific Gas and Electric, San Diego Gas and Electric, and Southern California Gas) to develop basic metrics for the qualitative comparison of existing diagnostic tools and those under development. The four metrics were:

- disruption of service (technique can take place while pipeline is in operation or online versus offline)
- frequency of data reporting (technique produces continuous or intermittent data
- cost, and
- size.

2.2 Existing Diagnostic Techniques

The researchers explored the following diagnostic techniques with respect to the four metrics outlined above:

- Hydrostatic Testing
    - using pressurized water to detect cracks in pipeline
    - offline, intermittent, expensive, large
- Pigs
    - using in-pipe devices with onboard sensors that travel through pipeline
    - offline, intermittent, expensive, large
- Common Pipe Wall Diagnostic Techniques
    - Magnetic Flux Leakage
        - apply magnetic field and observe anomalies

        - offline, intermittent, inexpensive, small
    - Eddy Current Testing
        - electromagnetic technique used for crack and defect detection
        - online, intermittent, inexpensive, small
    - Ultrasonic Testing
        - use ultrasonic transducers to measure pipe wall thickness and detect cracks
        - online, intermittent, expensive, small
    - Electromagnetic Acoustic Transducer
        - new ultrasonic technique to measure pipe wall thickness and detect cracks
        - offline, intermittent, small
- Existing Benchmarking Sensors
    - Vibration
        - online, continuous, inexpensive, very small
    - Flow
        - online, continuous, expensive, large
    - Moisture
        - online, continuous, inexpensive to expensive, small
    - Odorant
        - online, continuous, expensive, large

2.3 Conclusion

- The most common diagnostic techniques were intermittent data reporting or requiring offline operation (which requires a costly disruption of service).
- Most off-the-shelf sensors were expensive, preventing ubiquitous deployment.
- Two types of the off-the-shelf sensors that stood out for potential development at the MEMS scale were the vibration sensor and MEMS flow sensors.

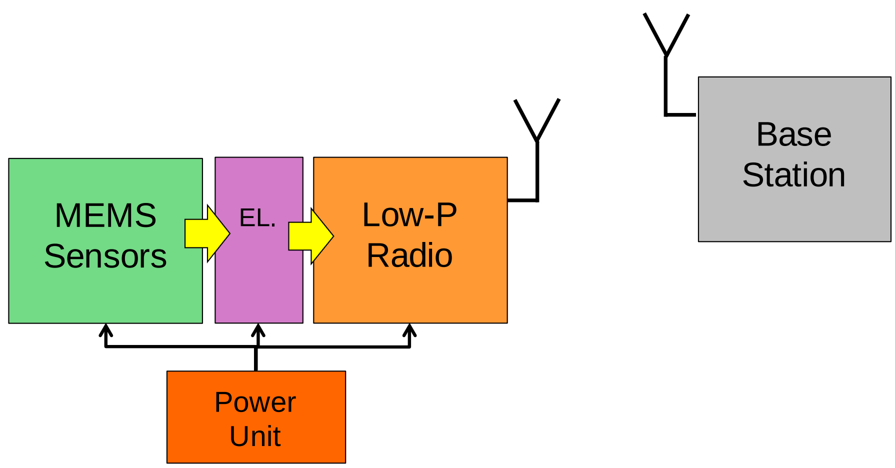
CHAPTER 3:
Design Gas Pipeline Sensors

Two gas pipeline sensors were designed. After conducting a needs-assessment analysis, the research team focused this project on four types of sensors: low-cost and low-power MEMS pressure sensors, MEMS flow sensors, MEMS accelerometers and Laser Ultrasonic Testing. See Appendix B for the full report.

3.1 Gas Pipeline Sensor Design

The proposed system design of the wireless sensor modules is based on similar self-powered sensor modules previously developed. The schematic of the MEMS sensor module is shown in Figure 1. The sensor module consists of MEMS sensors (green), which measure pressure, flow, and acceleration, a set of operational amplifiers and electronics (magenta) that convert the signal from the sensors to a signal that can enter the wireless radio (orange). A power unit, which is some combination of a battery and an energy scavenger (red), provides the energy for the radio, the electronics, and the sensors. A base station receives the information from many sensor modules and provides a gateway between the sensor modules and the backbone information network for the utilities, such as the Advance Meter Infrastructure.

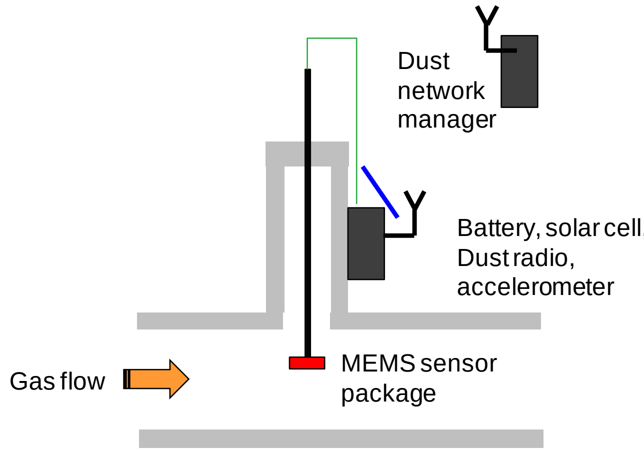
Figure 1: Schematic View of the Sensor Module



Source: UC Berkeley

Based largely on input from the utilities, the research team designed two types of implementation of the sensor modules in natural gas pipelines. The baseline implementation relies on existing access points, such as valve stations. The design of a sensor at such an access point is shown in Figure 2.

Figure 2: Sensor Modules at Valve-station Access Point



Source: UC Berkeley

The advanced implementation of the sensor modules involves a set of wireless MEMS sensor modules inserted through the access point. The modules are pushed by the gas flow and are designed to distribute themselves along the pipeline to form a wireless mesh network. The research team will focus on the first implementation.

3.2 Miniaturized Electro-Mechanical System Sensor Designs

Based on the needs analysis, including surveys and interviews with the utilities, the following sensor concepts were deemed useful for natural gas pipeline diagnostics:

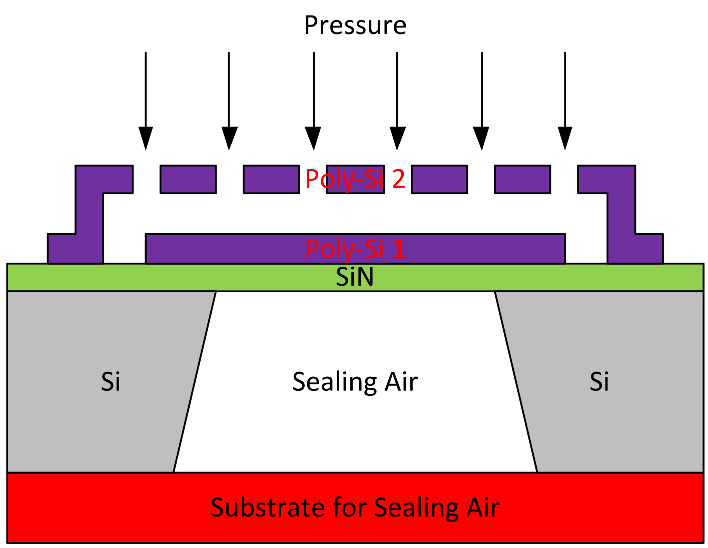
- **Inexpensive pressure sensors:** Low-cost pressure sensors that can be deployed to monitor the pressure on the pipeline, detect line breaks and pressure spikes.
- **Inexpensive flow sensors:** Flow sensors that can measure the amount of flow through the pipeline. Currently not all valve stations are metered. Inexpensive flow meters could potentially detect leaks (difference in net flow), and other abnormalities.
- **Vibrations:** Able to detect when something slams into the pipeline and if there is a rupture. Also detects earthquakes. A break in the line could be detected by nearby vibration sensors.
- **Moisture:** Moisture in the line causes corrosion. Humidity sensors can measure the moisture content within the gas, and detect conditions that over time will cause degradation of the pipeline. Also important to detect accumulated hydrocarbons in the line, that will cause degradation as well.
- **Level of Odorant in the gas:** Inexpensive sensor that can measure the level of odorant in the gas. Reduced levels of odorant are dangerous, if odorant falls below 4 parts per million (ppm), the natural warning system for leaks (nose) will not work.
- **Methane:** Detect line breaks by detecting gas (methane) at the surface.

Based on the limited time, the research team decided to focus on the following three sensors concepts: 1) low-cost MEMS pressure sensors, 2) low-cost MEMS flow sensors, and 3) vibration sensors.

3.2.1 Pressure Sensors

A capacitive pressure sensor uses a diaphragm and a pressure cavity to create a variable capacitor to detect strain due to applied pressure (Figure 3). The change in capacitance can be measured and translated to a pressure reading.

Figure 3: Schematic View of the Capacitive Pressure Sensor.



Source: UC Berkeley

The research team also explored the potential of piezo resistive pressure sensors, but since these consume more power, the team did not pursue this design.

3.2.2 Flow Sensors

A heat-flux based flow sensor consists of a heater filament, which produces heat in the surrounding gas. When there is no flow, temperature distribution is uniform, but with flow, the temperature at the side of the heater facing the flow cools and the side away from the flow warms. The temperature distribution skews in the direction of the flow. A thermopile, an electronic device that converts thermal energy into electrical energy, can measure this difference and translate to a mass flow velocity and mass flow rate.

3.2.3 Vibration Sensors

A MEMS accelerometer uses the concept of a suspended mass, which movement is then tracked through microelectromechanical structures, and the relative motion of the device is registered. Off-the-shelf accelerometers are available for use in MEMS sensor modules.

3.3 Laser Ultrasonic Testing

Laser Ultrasonic Testing (LUT) is a decades-old non-contact method of ultrasonic detection used for testing material properties of objects that are strongly contoured. In LUT, a pulsed high-power optical laser beam is directed at the material under test. The beam is partially reflected and partially absorbed, thus rapidly heating a thin region at the surface of the material. A thermal stress is generated, causing the irradiated region to act as a transducer that launches an ultrasonic wave that propagates into the body of the material. If that ultrasonic wave encounters a discontinuity, such as a void in a weld, it is reflected back to the initially heated surface, causing that surface to deform. A second, lower-powered laser can detect the motion of the deformed surface and permit one to form an image showing the presence of the internal void.

Laser Ultrasonic Testing measure can measure:

1. Dimension properties (such as thickness) and density
2. Mechanical properties such as strength, ductility, fracture toughness, magnitude of residual stresses
3. Surface properties, roughness
4. Presence and size of all defects and discontinuities, such as cracks, inclusions, porosity
5. Quality and strength of interfaces, bonds, joints, including welds

The research team met with the local utility that is making “crawlers” to inspect gas pipelines. These crawlers could potentially accommodate the ultrasonic generation and detection lasers. The research team will work with local companies to explore this possibility.

3.4 Conclusions

- The research team developed the communication infrastructure around the MEMS sensor module.
- The team will fabricate low-cost MEMS pressure and flow sensors, and use an off-the-shelf MEMS accelerometer for vibration detection.
- The research team will work with commercial laser ultrasonic companies to explore a LUT sensor package that can be mounted onboard a robotic crawler to perform pipeline inspection.

CHAPTER 4: Workshop

On August 7, 2012, the California Energy Commission hosted a Natural Gas Pipeline Research Workshop at the offices in Sacramento, entitled Potential Pipeline Inspection Technologies for Upcoming Natural Gas Pipeline Research Solicitation. The UC Berkeley research team, members of the Gas Technology Institute, members of utilities, California Energy Commission staff, and other interested parties were present. The workshop announcement may be found in Appendix C, notes taken from the workshop in Appendix D, and the presentation slides from the UC Berkeley research team are found in a separate attachment.

The purpose of the workshop was two-fold, given the amount of pipeline in California that run through high population areas: one, to discuss research, development, and demonstration opportunities to improve integrity management practices (IMPs), and two, to develop and bring to market cost effective technologies that increase system awareness, reliability, and provide tangible benefits to California ratepayers.

Members of the Gas Technology Institute (GTI) described the California Energy Commission-funded GTI research on identifying and categorizing current applicable technologies and interviewing operators to assess current safety practices and needs. GTI outlined necessary future steps, such as workshops and education, and outlined action plans at different time scales, such as a rapid deployment, 12-month plan, and 12-24 month plan.

Members the UC Berkeley research team described the relevance of low-cost, low-power miniature sensors, namely the pressure, flow, and vibration sensors. The team outlined the sensors module package, with infrastructure to transmit data in real-time.

A panel then discussed prioritizing areas of emphasis for solicitation of proposals:

- Enhanced operational awareness using low-cost/low-power sensors
- Integrating multiple crack inspection devices on a single pipeline crawler
- Methods to reduce operating costs and optimize field data collection
- Enhanced Integrity Management Practices through risk analysis, prediction, and decision based methodology

CHAPTER 5:
Laboratory Testing of Gas Pipeline Sensor Prototypes

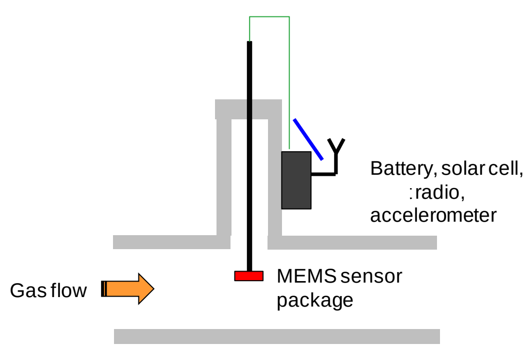
Prototype sensors were tested in a laboratory setting, including evaluating the operational characteristics of the sensors, such as calibrations and best distance for data transmission, and establish baseline metrics. This summary discusses the specific technology selections pursued by the research team and outlines the laboratory test results (modeling) during the development of the low-cost sensor package, including impact alarm testing, data transmission metrics such as sensor payload packet loss, and pressure sensor data. Low-cost MEMS sensors can be fabricated at a price tag of below $18 that can measure both pressure and flow with the accuracy of a few percent; this demonstrates that it is possible to instrument a valve station with flow, impact, and pressure sensors for below $70 per node, and $500 per valve station. Finally, the report discusses the project team's investigation of LUT for measuring pipe wall thickness and the use of ultrasonic acoustic waves for gas flow measurement. The LUT method is a viable way of non-contact probing of the welds and defects in natural gas pipelines. The ultrasonic flow measurement, although at an early stage of the development, is also a promising potential method for flow measurements in natural gas pipelines. Overall, the laboratory data indicate that it is indeed possible to develop low-cost wireless sensor packages that form wireless networks that can increase the safety and reliability of natural gas pipelines at a cost that enables their wide deployment. The full report may be found in Appendix E.

5.1 Test procedure

5.1.1 Sensor Package Testing

In order to evaluate the designs for the monitoring system, several sensor nodes were constructed with off-the-shelf components while the MEMS devices were fabricated. Figure 4 shows the proposed configuration of the sensor node.

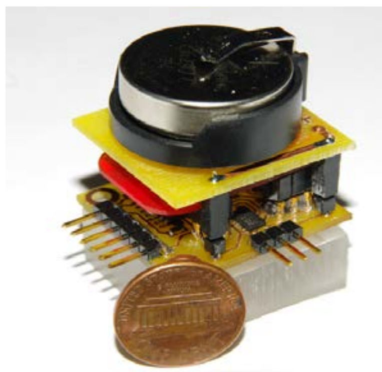
Figure 4: The Sensor Modules at Valve-Station Access Point



Source: UC Berkeley

The nodes consist of microcontrollers with radios, both from Texas Instruments, as well as from a MEMS accelerometer and interface circuitry for the pressure sensors (Figure 5). Power is currently provided by a 1,000 milliamp-hour (mAh) coin cell, which, depending on the software configuration and desired data output, will last from a few weeks to a few months. If the system were deployed in the field, alternate power supplies or larger batteries would be installed. The node below shows the radio (red, just visible), sensor interface and accelerometer (bottom circuit board) and coin cell power supply.

Figure 5: Node, With Radio, Sensor Interface and Accelerometer and Coin Cell Power Supply



Source: UC Berkeley

The research team tested the devices by running several of the nodes in a star network, monitoring packet loss rates, and recording sample data. Both acceleration (impact alarm) and pressure data were recorded. These data, presented in the following sections, indicates that low-cost mesh networking with inexpensive sensors is a feasible method for low-cost instrumentation of natural gas pipelines.

5.1.2 Impact Alarm Testing

To simulate impacts against a pipeline, the nodes were installed on a 6-inch diameter aluminum pipe in the lab and identical impacts were applied adjacent to each node. Data were recorded with the access point connected to a laptop at three different distances from the sensors. An "event" is defined as an impact sufficient to trigger an "alarm". The results showed that the impact alarm triggers the accelerometer reliably; however, some data packets are lost. If acknowledgements were added to the transmitted packets, this would ensure that the transmitting node retransmits the alarm packet until it receives an acknowledgement message.

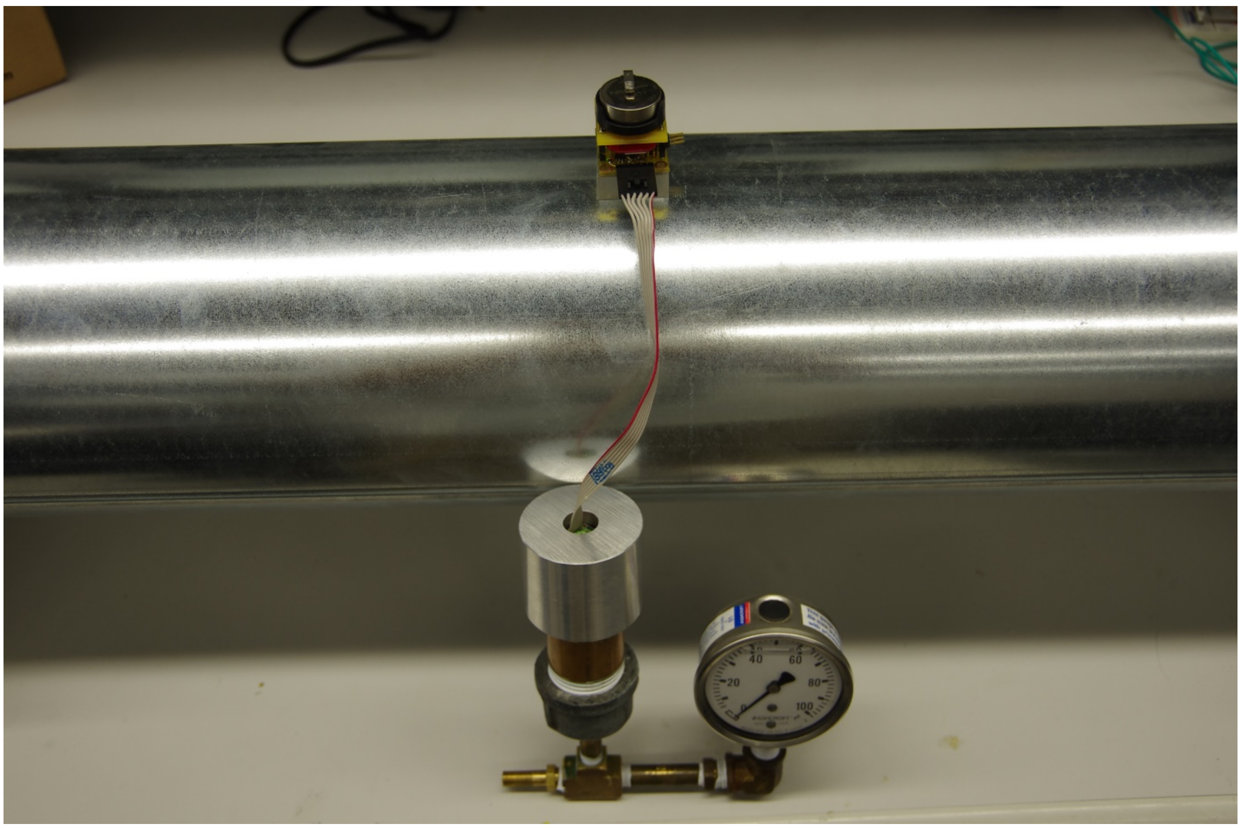
5.1.3 Sensor Payload Packet Loss

To test the performance of the network while continuously transmitting sensor data, four nodes were operated on the same network while transmitting simulated sensor readings once every second. The distance to the access point was varied by transporting the laptop around the lab during the test, and ranged on average from about 2 to 10 feet. Packet loss is measured by counting consecutive packet identifications (IDs) and determining whether there are gaps in the numerical sequence. The results indicated that packet loss rates are quite low, and a simple acknowledgement scheme would likely be sufficient to eliminate lost packets without affecting the performance of the network.

5.1.4 Pressure Sensor Data

Pressure measurements were taken using a commercial 500 pounds per square inch (psi) sensor. The sensor was placed in a custom pressure vessel that can be pressurized using available shop air to about 100 psi. An image of the pressure sensor is shown in Figure 6.

Figure 6: Pressure Vessel Connected to a Node



Source: UC Berkeley

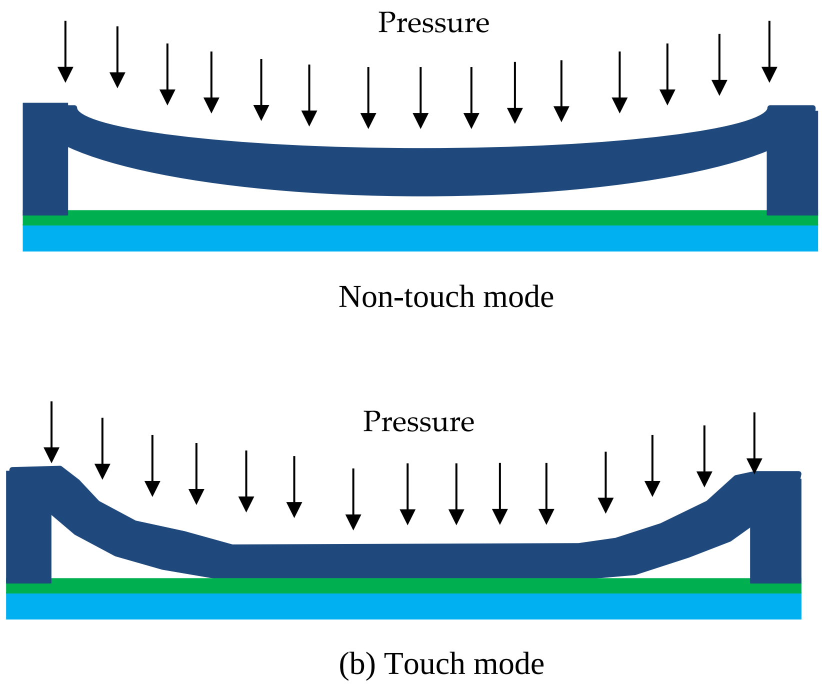
The results demonstrate the ability of the sensor package system to reliably record pressure readings and measure pressure fluctuations once every second.

As the low-cost MEMS pressure and flow sensors were still undergoing fabrication, the next two sections present the MEMS sensors analysis using finite element methods (FEM) to calculate the sensitivity of the MEMS sensors. Both the pressure and flow sensor designs are using capacitive transduction, which is characterized by low power consumption, low noise, and especially low thermal sensitivity when compared with piezo resistive or thermal transducers. These capacitive MEMS sensors are therefore more suitable for outdoor applications, in which the temperature depends on the weather condition.

5.2 Test Results of Pressure Sensors

The capacitive MEMS pressure sensor is a pressure-sensing diaphragm on a silicon (Si) substrate. When external pressure is applied to this sensor diaphragm membrane, the membrane deflects towards the bottom electrode and the effective capacitance increases. Silicon Carbide (SiC) was selected as diaphragm membrane due to its high tensile strength when compared to poly-Si. There is a dielectric layer Si_3N_4 between two electrodes to ensure the sensor operates in the touch-mode (that is, when the diaphragm membrane makes contact with the bottom electrode) compared to non-touch mode (Figure 7).

Figure 7: Diaphragm of Pressure Sensor in Non-Touch Mode and Touch Mode.

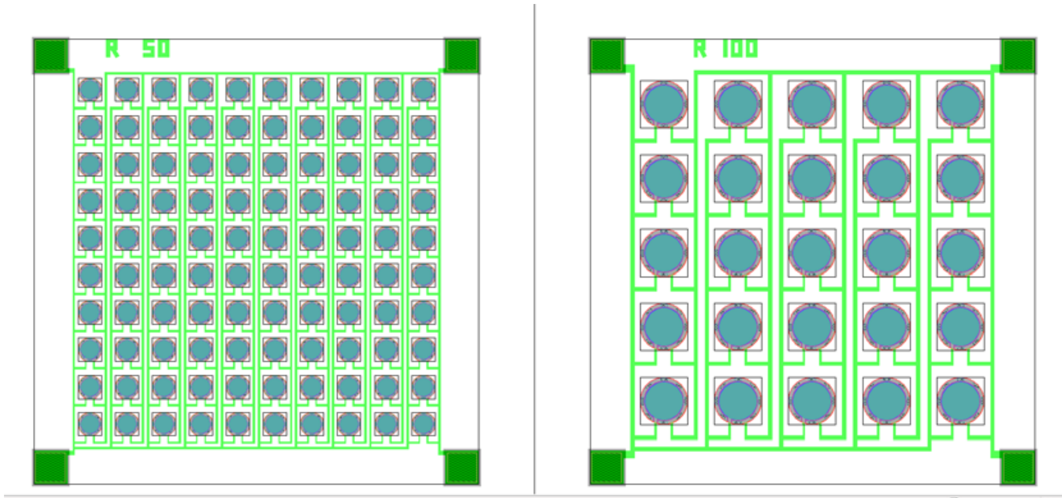


Source: UC Berkeley

By designing pressure sensors that operate in touch mode one can increase the measured pressure range by 40 times compared to sensors in non-touch mode; however, touch-mode pressure sensors show nonlinearity.

Figure 8 shows the layout mask for capacitive MEMS pressure sensors. To increase the variable capacitance, the researchers designed two arrays of pressure sensors. An array of 25 pressure sensors gives a variable capacitance up to 30 - 40 picoFarads (pF) for pressure range of 200 psi to 1000 psi. An array of 100 pressures sensors in parallel is also designed.

Figure 8: Mask Layer of the Two Designs



Source: UC Berkeley

The FEM model shows that the pressure sensor can operate at high pressures in the touch mode. The sensor can work at a pressure of 1000 psi. However, the sensitivity of the sensors at high pressure is smaller compare to that at lower pressures. The resolution of the pressure sensor is estimated at approximately 10 psi.

The capacitive MEMS pressure sensors are fabricated by surface micromachining. The process requires six masks.

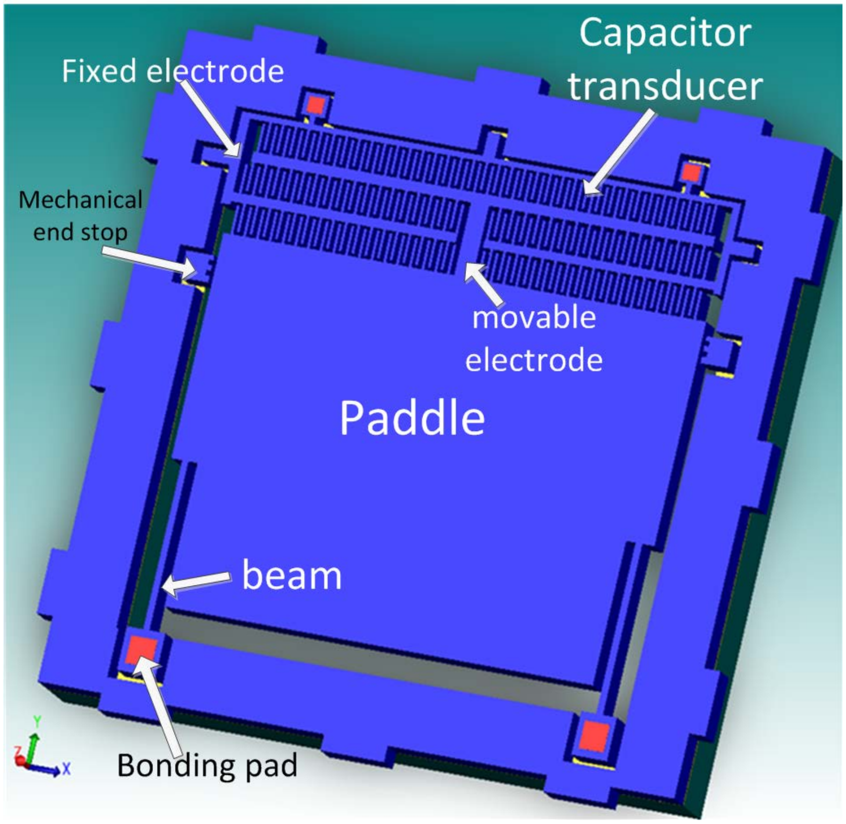
The research team can estimate the fabrication cost of the flow sensor by investigating the cost of its footprint based on a fixed cost of fabrication. For this analysis, the team assumed a conservative cost of a 300 millimeters (mm) size processed wafer to be $20,000, with usable area of 70,000 square millimeters, and a cost per square millimeter of $ 0.28. As the footprint of the sensor die is nine square millimeters, the cost of the pressure sensors is estimated to $2.82 per sensor.

5.3 Test Results of Flow Sensors

5.3.1 Design of Capacitive Flow Sensors

Figure 9 shows a three dimensional schematic drawing of a capacitive MEMS flow sensor. The sensor is designed to measure a maximum gas flow of about 15 meters per second (m/s) which is twice the typical velocity of pipeline gas flow (that is, 8 m/s). A paddle that is suspended by two beams moves due to the drag force under a gas flow in the perpendicular direction. Movable capacitor fingers are connected to the end of the paddle. The capacitance between fixed fingers and movable fingers will vary when the paddle moves because of the gas flow.

Figure 9: Schematic Drawing of the Capacitive Flow Sensor



Source: UC Berkeley

The paddle with its suspension is modeled in CoventorWare FEM to calculate the displacement under varying drag force. The drag force (F_D) is changed to pressure, that is drag force per unit area, to apply the load for the paddle.

The results indicate that the resolution of the sensor is about 0.3 m/s, or 2 percent of the full range.

The capacitive MEMS flow sensors are fabricated on silicon-on-insulator (SOI) wafers using bulk micromachining technologies. The advantage of the design is a simple fabrication process. It just requires three masks for the electrical ponding pads, top structures, and backside cavity.

Again, the fabrication cost of the flow sensor is estimated by investigating its footprint cost. The resulting cost per flow sensor die is estimated to $18 per sensor. However, this cost can be reduced by an order of magnitude using larger substrates in MEMS-on-glass technology, reducing the cost of the sensor to below $2.

5.4 Exploring Laser Ultrasonic Testing

This section discusses natural gas pipeline measurement techniques that employ elastic waves, having frequencies above the range of human hearing, that are propagating either in a solid (the pipe itself) or in the gas inside the pipe. Such ultrasonic waves may be used to determine properties of the pipe and to measure the flow velocity of the gas in the pipe. The full report describes assessing pipe integrity by using two different type ultrasonic approaches: using an electromagnetic ultrasonic transducer (EMAT) and using a laser ultrasonic testing system. It also discusses the use of micro fabricated ultrasonic transducers to monitor gas flow rate in a pipe. This flow measurement technique will function with flow in either direction.

Test results on sample welds, in addition to literature on the subject of laser ultrasonic testing, show that many characteristics of pipes can be determined using ultrasonic waves, such as defects in pipe walls and welds. Comparison of the results with the two samples show that one can detect a weld where penetration of the welding material is incomplete and welds of offset pipe sections can be detected. Laser ultrasonic testing can have a higher spatial resolution than is found with the much larger EMATs. A laser ultrasonic system could be mounted on a crawler and used to inspect welds and other important elements of ventilated gas pipelines, and could be used in pipes that are too small for the use of highly instrumented pigs. The ability of laser ultrasonics to size stress corrosion cracks in pressurized pipes has also been demonstrated, with a crack depth resolution of about 0.125 mm. Wall thickness variations, as would be caused by external pipe corrosion, can be measured by LUT with an error of only 1 or 2 percent.

The research team investigated and experimented with the use of efficient micro fabricated ultrasonic transducers that could be mounted in small side branches on a natural gas pipeline. These arrays of ultrasonic sending and receiving transducers are called "pMUTs", for "piezoelectric Micro fabricated Ultrasonic Transducers", and were originally conceived for detecting human hand gestures to control computers. The techniques have been shown to be effective in determining the flow when compared with anemometer measurements. Ultrasonic attenuation in methane is an issue as it may limit the diameters of pipes in which the present pMUTs can be employed; using two sensors in tandem may alleviate the attenuation problem while still providing accurate flow data. Further development of the micro fabricated transducers (that is, to increase the number of transducer elements that can be employed to increase their range, using a phased-array configuration to permit angular discrimination that would use a single sensor in a side-branch) could make the use of these transducers more attractive.

In conclusion, from the experiments and analysis to date, it appears that micro fabricated pMUTs can be used to measure gas flow rate in pipes up to 30 inches in diameter. For a given pMUT design, the accuracy of the measured flow rate depends upon the average flow rate (such as 8.3m/s) and the rapidity with which the flow rate is changing. Further analysis and newly designed pMUTs would enable one to estimate the accuracy with which flow rate can be measured.

5.5 Conclusions

- The laboratory tests of the sensor package, using a vibration sensor to detect impact and pressure sensor, successfully showed the accurate transmission of data, with low data loss.
- The team designed a diaphragm-based pressure sensor
- The team changed the heat-flux flow sensor due to the danger of sparking to a flow sensor with a paddle-like cantilever attached at one end that changes capacitance with flow.
- Initial estimations show that MEMS sensors can be fabricated for less than $18; it is possible to instrument a valve station with flow, impact, and pressure sensors for below $70 per node, and $500 per valve station.
- LUT is a viable approach for diagnosing pipelines when out of service
- The prototype micro ultrasonic sensors could measure flow for small diameter pipes (up to 30 inches) and may work in pairs for larger diameter pipes.

CHAPTER 6: Gas Pipeline Sensor Test bed

A test bed was needed to reliably pre-test the MEMS sensors previously developed in the project. This test bed provided an inert environment in a controlled laboratory prior to pilot deployment in the field.

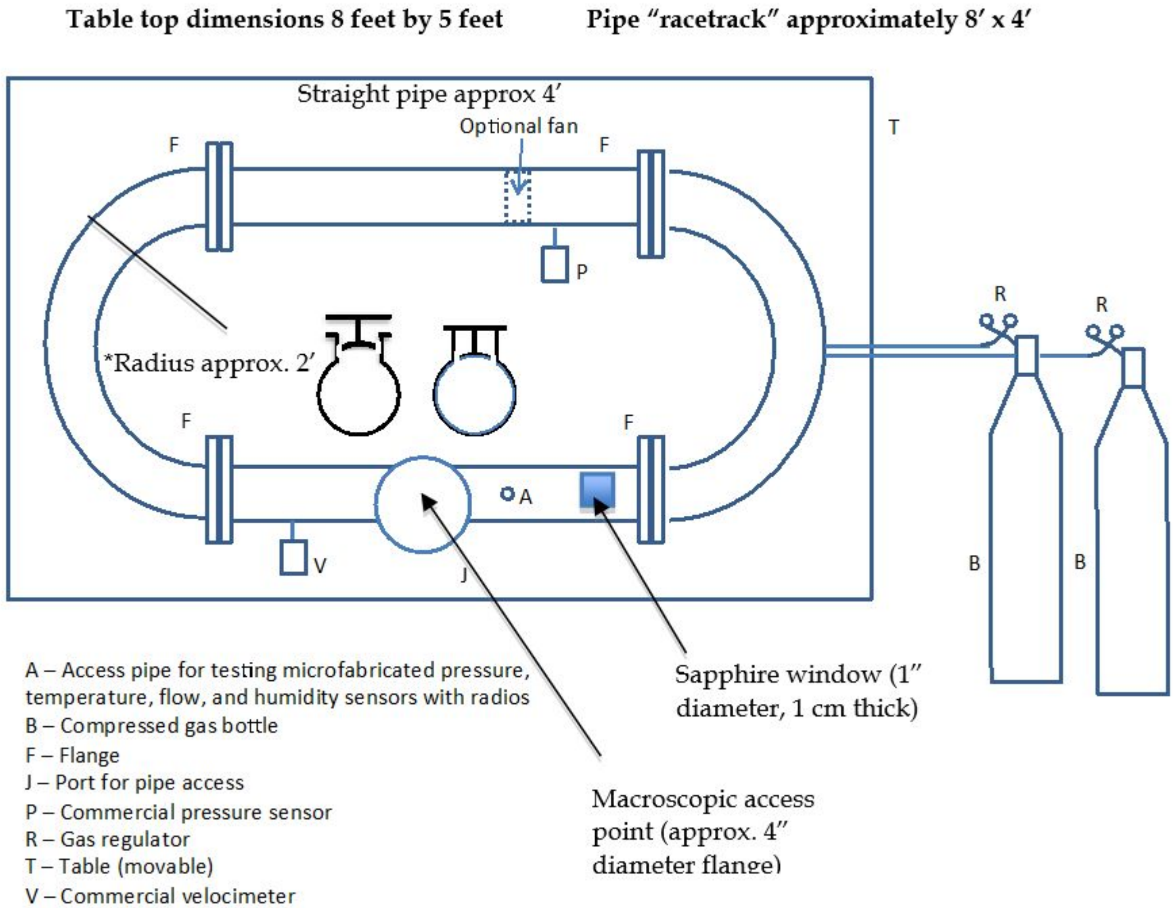
To ensure reliable performance in the field, the MEMS sensors developed by this project must be tested in a way that emulates the natural gas pipeline environment yet is safe and convenient for the researchers. Over the course of the project, the researchers found obtaining access to utilities' field test site was proving difficult and the cost for using a third party testing facility was found to be expensive ($6000 per day).

The objective of the test bed was to emulate field-testing conditions in lieu of field testing the prototyped MEMS sensors. The design process evolved through much iteration as the researchers discussed the design with the Professional Advisory Committee and several fabrication experts. The final "raceway" vessel is approximately 4 feet by 8 feet on a rolling table, with multiple components, such as an in-line fan, viewing window, compressed air cylinders, safety measures, and commercial flow sensors. This report briefly describes the bidding process and outlines the fabrication process and testing, and closes with the final installation of the test bed. The full report is included as Appendix F.

6.1 Design

The researchers developed an initial schematic and description of the fabrication of the test bed as shown in Figure 10:

Figure 10: Schematic of Test Bed.



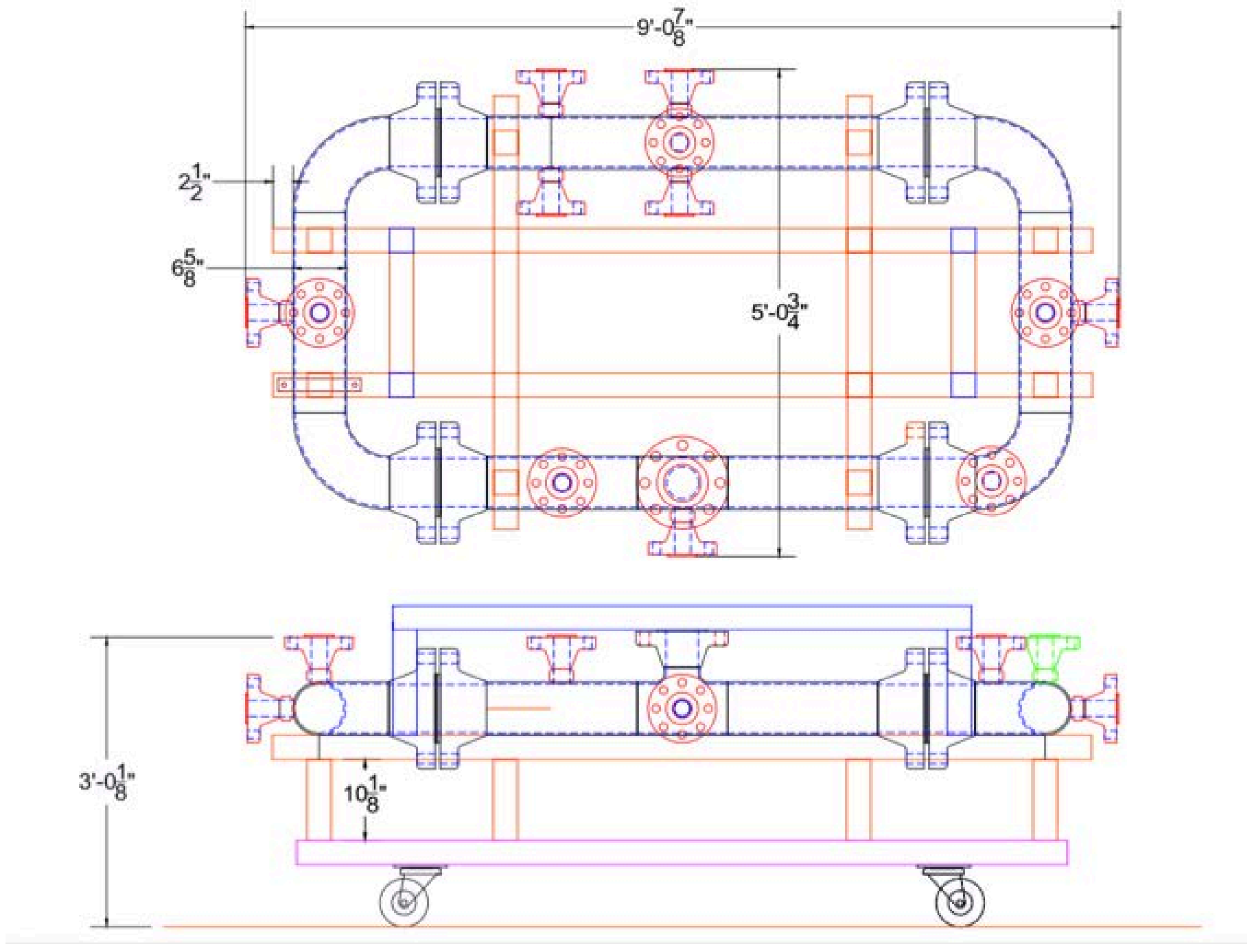
Source: UC Berkeley

The details included components (such as the pipe, fan, ports to insert the sensors, commercial meters to validate the sensors), safety features (such as bleed disks, pressure relief valves), and additional requirements (such as certified welders, hydro testing, means for purging the vessel).

The design changed slightly as the research team discovered more and more details on the components. The test bed design involved researching many individual components, such as commercial flow sensors, viewing ports, an in-line fan, and the feedthroughs (the electrical connections between the test bed and outside measuring instruments). Ultimately, the commercial flow sensor and flow straighteners or conditioners came from Sage Metering. This flow sensor can also be used with methane. Two inch fused glass optical windows were ordered from Rayotek Scientific. These windows are off-the-shelf components that are pressure rated to 4000 psi. Custom electrical feedthroughs were ordered from Douglas Electrical. Two feedthroughs were needed: one for the sensors to be tested, and one to supply the power to the motor. Both of these feedthroughs are to be embedded in a steel plate with a bolt pattern, which enables them to be bolted to the flanges at the ports. Both feedthroughs are rated to 2300 psi.

The final engineering drawings (plan and side elevation) are shown in Figure 11:

Figure 11: Final Engineering Drawings of the Test Bed.



Source: UC Berkeley

6.2 Fabrication

The UC Berkeley research team had several meetings throughout September, October, and early November 2013 discussing the test bed, and consulting with several entities (such as heads of the Mechanical Engineering (ME) and Electrical Engineering Computer Science (EECS) machine shops, environmental health and safety on campus). Initially, the researchers decided to have the test bed constructed off campus by subcontractors for lab safety and liability reasons. The liability regarding specialized welding of pressurized pipes was especially important to this decision, since the project requires certified welders contracted for the test bed construction. However, after receiving only two bids, the research team decided to have the test bed made at the EECS machine shop. Figure 12 shows the pieces of the test bed while in fabrication.

Figure 12: The Welded Curved Ends and Straight Sections of the Test Bed.

Source: UC Berkeley

6.2.1 Validation Tests

The test bed must undergo similar tests as natural gas pipelines. One test is pressure testing, and Spike methods, which use pressurized water to test the pipeline at Maximum Allowable Operating Pressure (MAOP) or several times greater than MAOP before it can go into service. Before the vessel can be pressure tested, it must undergo X-rays provide the ability to determine the integrity of the welds. Other tests are Magnetic Particle Inspection (for surface and slightly subsurface material discontinuity) and Dye Penetration Inspection (used to detect surface defects).

The test bed eventually passed all tests.

6.3 Installation

The pieces were delivered and assembled in nearby Davis Hall since it has a crane to ease assembly. The locked cabinet with the compressed air tanks is shown in the right corner of the Figure 13.

Figure 13: The Installed Test Bed in 143 Sutardja Dai Hall.

Source: UC Berkeley

6.4 Conclusions

- The team designed an inert test environment to emulate field conditions.
- The final "raceway" vessel is approximately 4 feet by 8 feet on a rolling table, with multiple components, such as an in-line fan, viewing window, compressed air cylinders, safety measures, and commercial flow sensors.
- The test bed passed several validation tests, including X-ray, hydro testing, and dye testing.
- The test bed and components were installed.

CHAPTER 7: Test Sensor Prototypes in Test bed

After building a test bed, the next step was to test the micro-electro-mechanical systems (MEMS) sensors in a safe convenient location for the researcher that still provides a realistic emulation of natural gas pipelines in the field.

The objective was to describe the procedure of testing the MEMS flow and pressure sensors in a test bed fabricated by UC Berkeley. The test bed is a “racetrack” oval (roughly four feet by eight feet) of six-inch diameter pipe that provides an inert laboratory environment to emulate natural gas pipelines in field conditions. The external ports of the test bed allowed researchers to insert the sensors into the test bed; electrical feedthroughs provide the infrastructure to measure the sensor output. The output of the sensors was compared with the output of commercial sensors. The full report may be found in Appendix G.

7.1 Test Procedure

Before the completion of the test bed, the researchers developed a method for the initial testing of the MEMS-based flow sensors (Figure 14). The main part of the apparatus consists of an open- ended 6-inch inner diameter air duct connected to a large fan. The configuration allows for flow variation through a transformer. A commercial anemometer is used to determine the achieved flow velocities and to provide a reference. After establishing these initial parameters, the anemometer is replaced by the MEMS-fabricated flow sensor. An Agilent precision LCR (inductance (L), capacitance (C), and resistance (R)) component analyzer is used to record the changes in capacitance of the flow sensor with respect to flow velocity. The data is recorded and visualized through a connection between the LCR meter and a personal computer. Given that these measurements are taking place in an open- ended section of pipe, the arrangement does not allow control over the internal pipe pressure and so the results are taken in atmospheric pressure.

Figure 14: Initial Measurement Apparatus for Flow Sensors

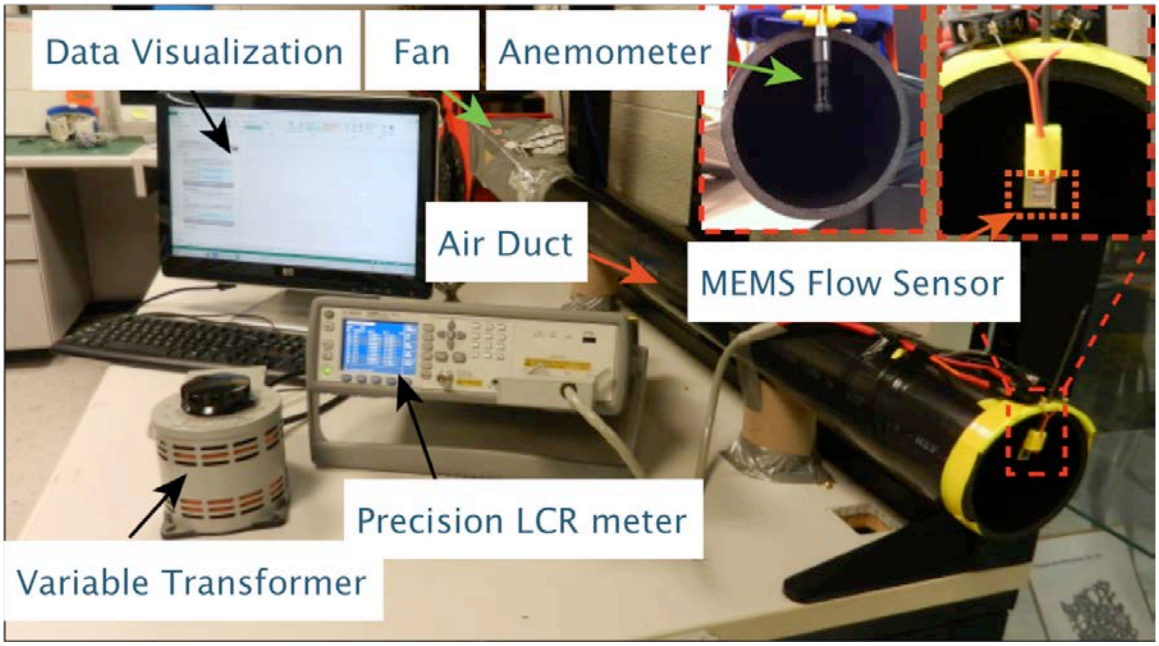


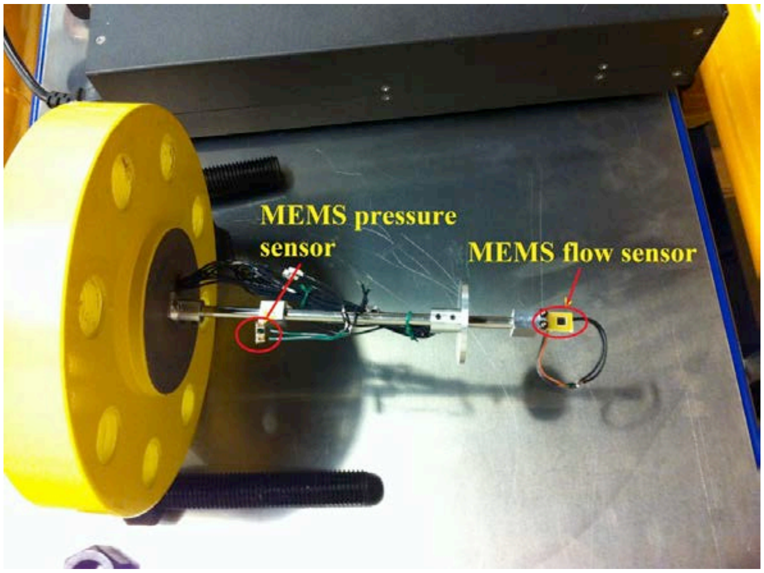
Photo Credit: UC Berkeley

The results of the experiment show very good agreement with the model prediction.

7.2 Test Results of Pressure Sensors

Figure 15 shows the arrangement of flow and pressure sensors as they are mounted inside the test bed. A metal rod has fixtures to accommodate both sensor types and the length is such that the flow sensor reaches the center of the 6-inch pipe. Furthermore, the electrical connections to the external measurement equipment are achieved through pressure resistant feedthroughs that go through the plate of the mounting flange.

Figure 15: Sensor Mounting for Experiments Inside the Test Bed



Source: UC Berkeley

The reference pressure gauge is depicted in Figure 16. It is mounted onto the flange closest to the sensor insertion point and gives a direct reading of the pressure inside the test bed. It is important to note that the dial indicates the pressure in gauge pressure per square inch (psig), meaning that a pressure of 0 psi indicates atmospheric pressure.

Figure 16: Reference Pressure Monitor

Source: UC Berkeley

Figure 17 depicts the electrical connection to the same precision LCR component analyzer described above by clamping to the cable coming out of the high-pressure feedthrough. This piece of equipment enables measuring of the capacitance changes of the MEMS pressure sensor in relation to a pressure increase in the pipeline test bed as monitored by the reference pressure gauge.

Figure 17: Precision Component Analyzer and Electrical Feedthroughs for the Sensors.

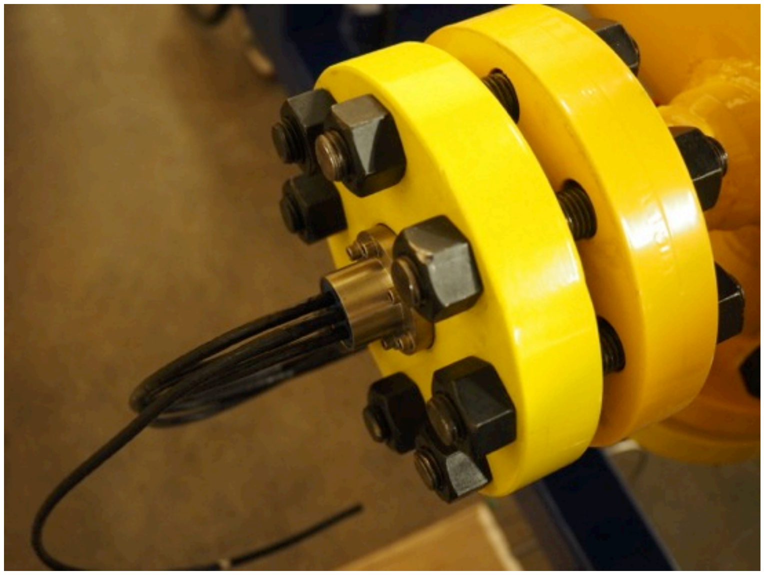
Source: UC Berkeley

7.3 Test Results of Flow Sensors

An internal fan is installed inside the test bed in order to generate flow at pressure for testing of the miniature MEMS-based flow sensors. The internal fan operates on Direct Current (DC) power and is specified to be able to withstand 5 kilowatts of power.

The connections to the fan motor are again accomplished through pressure resistant feedthroughs, seen in Figure 18.

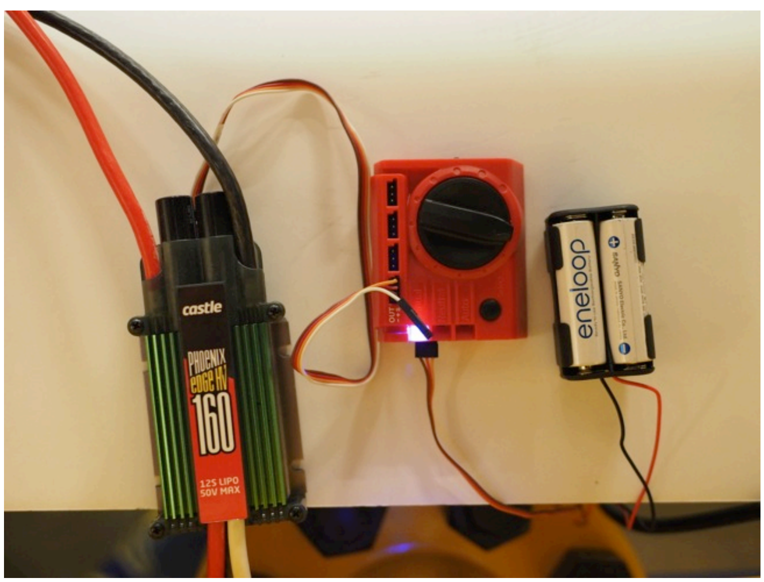
Figure 18: Electrical Feedthroughs for the Internal Fan Motor



Source: UC Berkeley

The fan speed can be adjusted continuously through the Electronic Speed Control (ESC) system, as shown in Figure 19.

Figure 19: Electronic Speed Control for the Internal Fan



Source: UC Berkeley

Finally, Figure 20 depicts the arrangement of a commercial, insertion based reference flow meter by Sage Metering.

Figure 20: Commercial Reference Flow Meter

Source: UC Berkeley

7.4 Conclusions

- The external ports of the test bed allow researchers to insert the sensors into the test bed.
- Electrical feedthroughs provide the infrastructure to measure the sensor output.
- Compressed air provides pressure.
- An in-line fan provides flow in the test bed.
- Commercial pressure and flow sensors provide a means of validating the prototyped sensors.

CHAPTER 8: Data Analysis of Sensor Testing

Once the sensors were tested, the next step was to analyze the data collected in the test bed and in the field, including sensitivity, accuracy, reliability, and performance. The following describes the analysis of the sensor testing solely in the test bed, since field testing was not possible. The test bed is a "racetrack" oval (roughly four feet by eight feet) of six-inch diameter pipe that provides an inert laboratory environment to emulate natural gas pipelines in field conditions. The output of the sensors was compared with the output of commercial sensors. The analysis included sensitivity, accuracy, and reliability.

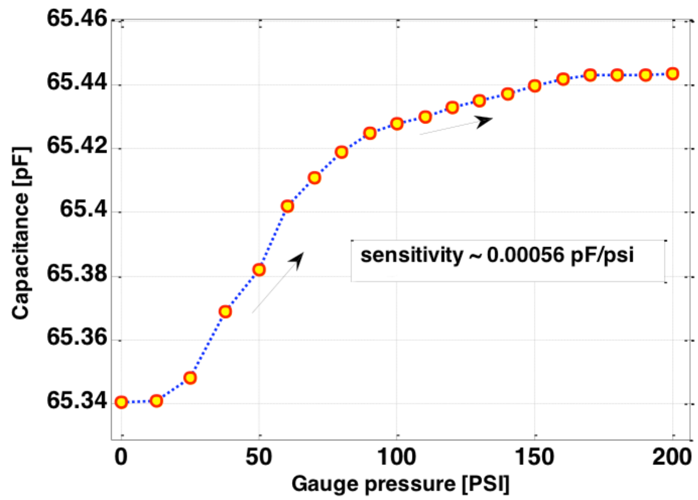
The initial test results of the pressure sensors revealed two issues: low sensitivity and an unexpected difference in output between increasing pressure and decreasing pressure. The researchers hypothesized these issues stemmed from a leak in the seals around the diaphragm, and modified the design. The subsequent testing of the pressure sensors showed that the design modification fixed both issues. The data showed appropriate sensitivity, and accurate measure of pressure whether under increasing or decreasing conditions; repeatability of these tests indicates the reliability of the pressure sensors.

The initial tests of the flow sensors found that particles from the interior of the test bed disrupted the measurement; future designs of this sensor may use magnets to eliminate the typical iron particles from interfering with the flow sensor mechanism. The full report is in Appendix H.

8.1 Analysis of Pressure Sensor Test Data

The first test of the pressure sensor in the test bed indicated a problem with the sensor. Figure 21 shows that the general shape of the curve matches the simulation model. However, the increase in capacitance is only in the order of 100 femtofarads (fF). Furthermore, the curve only starts at approximately 65.34 pF. The result is a low sensitivity (0.00056 pF/psi) of the measurements. Such small changes in capacitance are difficult to record accurately.

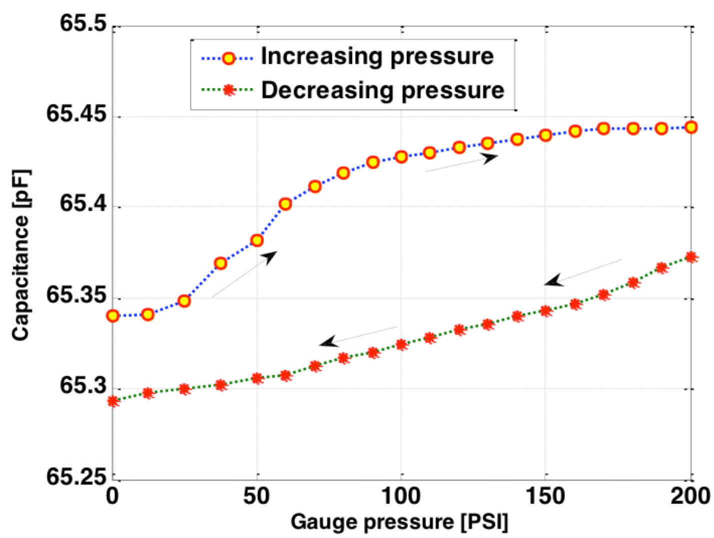
Figure 21: Experimental Data of Capacitance When Increasing the Pressure



Source: UC Berkeley

In addition, Figure 22 shows the result of an experiment, where the pressure was first gradually increased from 0 to 200 psi. Then, the pressure inside the test bed was kept at 200 psi for 20 minutes, before gradually releasing the pressure. A substantial drop in capacitance of about 70 fF on the MEMS sensor can be seen in the graph. This is unexpected as the reference pressure sensor on the test bed indicated a constant level of 200 psi during this period. The results show a strong hysteresis for the pressure release as compared to the pressure increase.

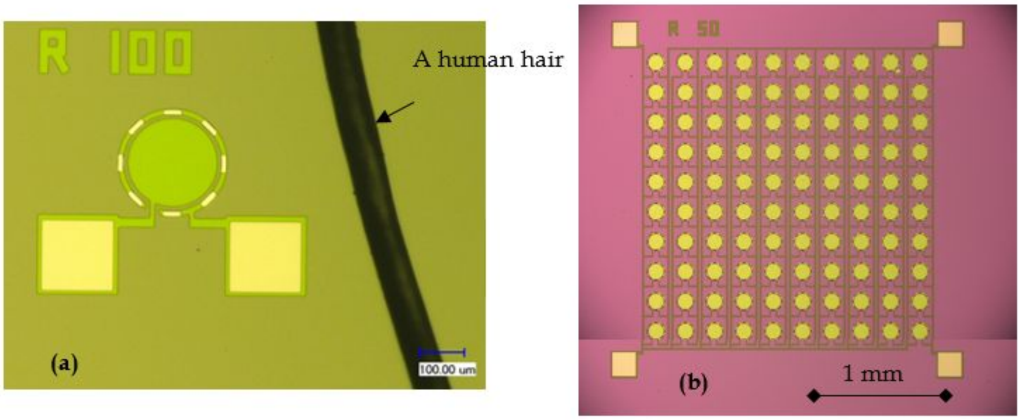
Figure 22: Experimental Data of Capacitance When Changing Pressure



Source: UC Berkeley

One hypothesis was that the seal was leaking. To review the design, the pressure sensor is composed of an array of small, round pressure capsules that have a vacuum inside (Figure 23). Under pressure, the top membrane deflects inwards and the capacitance between the bottom electrode and this top membrane changes as a consequence.

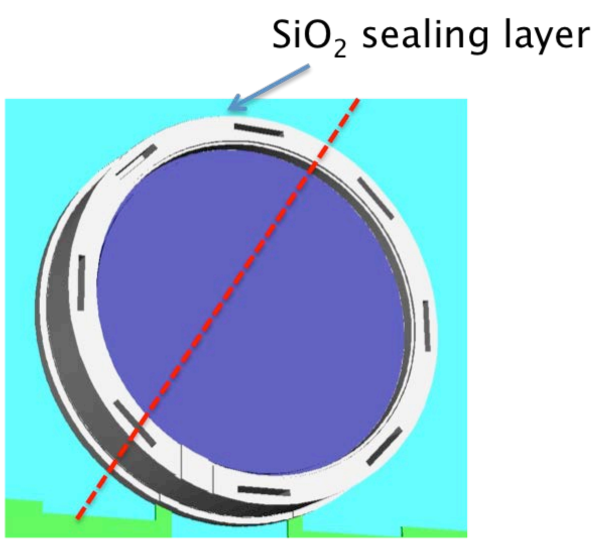
Figure 23: Miniature Pressure Sensor Layout



Source: UC Berkeley

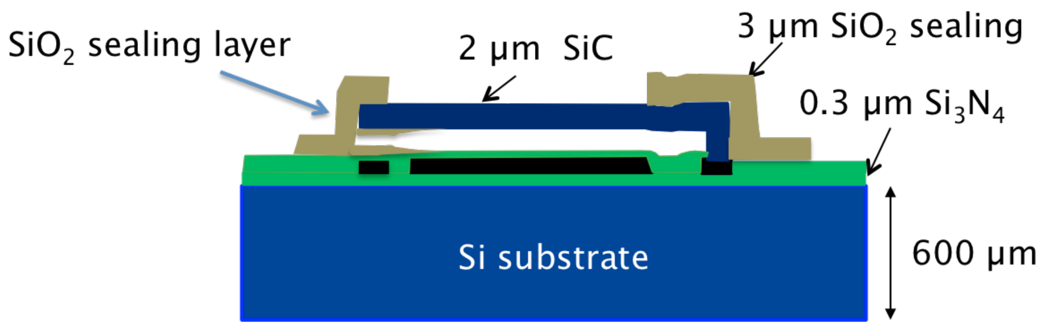
Figure 24 shows a magnified schematic of a single pressure capsule. Silicon dioxide (SiO_2) serves as a sealing layer to close the internal vacuum against the external pressure. The dashed red line indicates a section cut as it can be seen in Figure 25.

Figure 24: Schematic of a Single Membrane Arrangement of the Miniature Pressure Sensor



Source: UC Berkeley

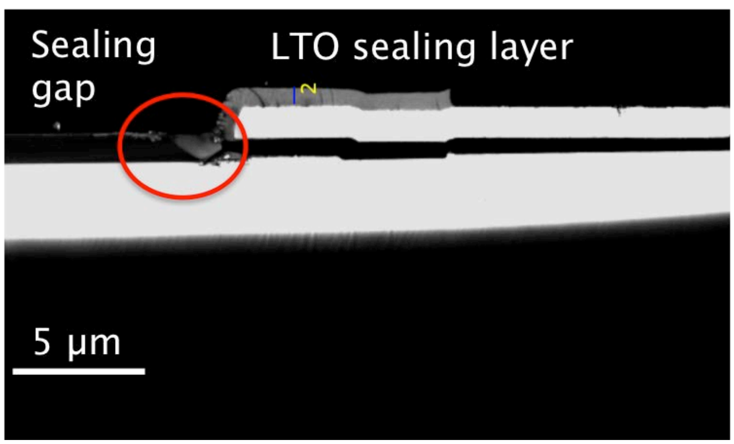
Figure 25: Cross Section of a Single Pressure Sensor Membrane at the Dotted Line in Figure 24



Source: UC Berkeley

Figure 26 shows a cross section view of an actual pressure sensor with the Low Temperature Oxide (LTO) layer, the membrane and the substrate. A void in the sealing can easily be discerned.

Figure 26: Micrograph of Cross-Section of a Pressure Sensor



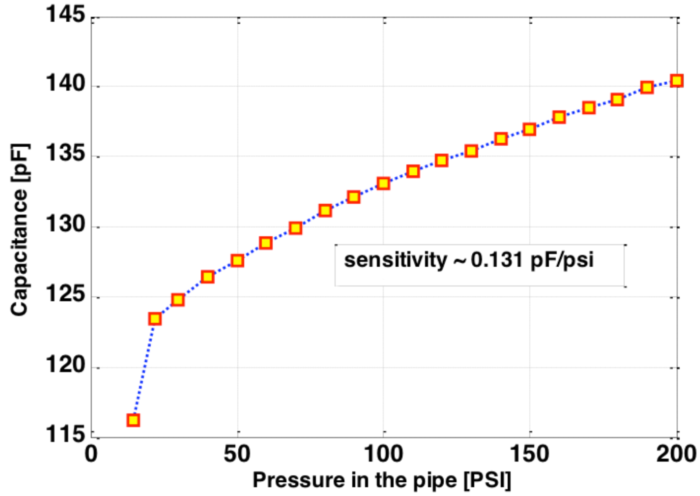
Source: UC Berkeley

As a result the fabrication process for the MEMS pressure sensors was adjusted. The second layer of silicon nitride (Si_3N_4) was omitted and the thickness of the oxide sealing layer was increased.

8.1.2 Updated Pressure Sensor Results

The previously discussed changes in the device fabrication have a dramatic effect on the achieved experimental results from the pressure sensors. Figure 27 shows an experiment with an increase in pressure as it was shown before but with the improved pressure sensor. The initial capacitance has now increased to about 114 pF, which is believed to be due to a reduction in parasitic capacitance as a consequence of the improved processing. The measurement range now shows a difference of 23.3 pF, which is two orders of magnitude larger than the previous experiment and better than the simulation prediction. This dramatically increases sensitivity (0.131 pF/psi) of the sensors and makes readout far less complicated.

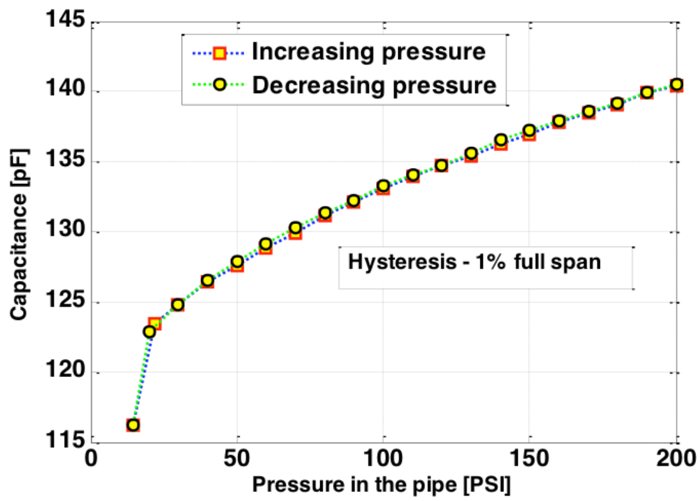
Figure 27: Updated Pressure Sensor Data



Source: UC Berkeley

Additionally, Figure 28 shows the same experiment that was conducted earlier, where the pressure is first increased inside the test bed and then held at 200 psi before being released. There is no discernible hysteresis anymore and the results for an increase and a decrease in pressure match very closely with only a 1% difference.

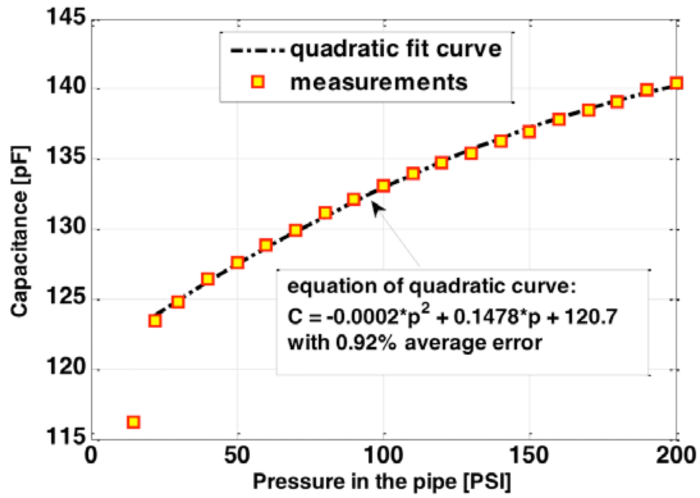
Figure 28: Data for Updated Sensor During Changing Pressure



Source: UC Berkeley

The quadratic curve fit to the experimental data (Figure 29) is more accurate with only a 0.9 % average error compared to 3.3 % average error for the linear fit.

Figure 29: Quadratic Curve Fit



Source: UC Berkeley

8.2 Analysis of Flow Sensor Test Data

The initial tests of the flow sensors in the test bed found that particles from the interior of the test bed got caught in the fine capacitor fingers of the flow meter. While the flow sensor function was shown in the laboratory, the flow sensor has not rendered data in the test bed. The research team discussed the redesign of the flow sensor as a potential fix. Future designs of this sensor may use magnets to draw the typical iron particles away from the flow and prevent particles from interfering with the flow sensor mechanism. Another potential solution is to coat the entire sensing area in an insulating material that would prevent conductive particles from shorting out neighboring capacitor fingers.

8.3 Conclusions

- Initial results from testing the pressure sensors showed problems caused by defects in the sealing of the pressure capsules.
- The fabrication process was adjusted to improve this sealing, resulting in great sensor performance, reproducibility and sensitivity in the updated device.
- For the flow sensors, the problem was iron particles caught in the capacitive fingers of the sensor.

CHAPTER 9: Miniaturization and Lifetime Testing and Public Workshop

There remained two more activities: a report to discuss the further miniaturization of the sensors and the accelerated lifetime testing of the sensors and a public workshop to disseminate the results. The report is described in this chapter and in Appendix I. The workshop is described in Appendix J.

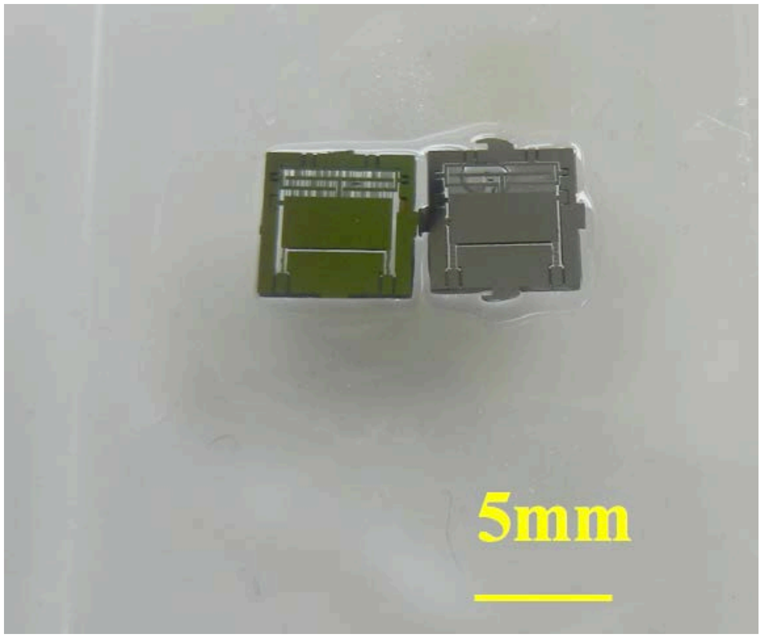
The objective was to refine the designs of the sensors for optimum production, resilience in the field (especially with respect to erosion and temperature ranges), and explore low-cost insertion techniques.

With regard to further miniaturization, the researchers concluded that the 5 millimeter by 5 millimeter dimensions of each sensor are already very small and could only be reduced by a significant effort in fabrication process and tool development. The researchers decided not to perform aggressive erosion testing in the test bed due to concerns over internal damage and safety. Thus, accelerated erosion testing was performed using sandblasting equipment; the Silicon Carbide coating on the flow sensor dramatically reduced the erosion damage. The flow sensor was tested at temperatures ranging from 23-43 °C, at three different air flow rates; the output differed by less than 0.5%. The researchers explored several options for inserting these MEMS sensors into a natural gas pipeline, such as hot tapping (inserting a test point site while the pipe is in service) and Smart Balls (foam balls with acoustic sensors that float through the pipeline). The researchers concluded that the current access points at valve sites and metering stations are appropriate for inserting the MEMS sensors.

9.1 Further Miniaturization

As can be seen in Figure 30, the dimensions of the MEMS flow sensor die are about 5x5 mm. The dimensions for the pressure sensor are similar to this. These dimensions are already very small and could only be reduced by a significant effort in fabrication process and tool development. The masks that are used for the current versions could not be utilized any longer and a complete redesign and financial investment would be required. Furthermore the advantages of further downscaling are considered very small with regards to the potential risks of decreased sensitivity and durability.

Figure 30: Close-Up of Sample Preparation of Flow Sensors



Source: UC Berkeley

9.2 Accelerated Lifetime Testing Results

The sensors were tested to ensure resilience in the field, especially with respect to erosion from abrasive particles and temperature fluctuations.

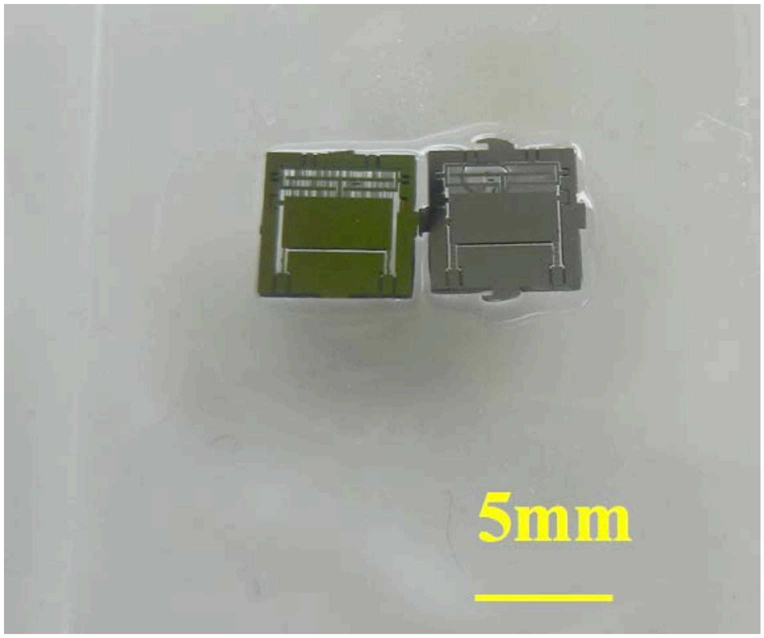
9.2.1 Abrasion

The main concern for sensor operation inside pipelines is the presence of abrasive particles such as sand that are carried by the flow. The flow sensors are at a greater risk because they are positioned in the center of the pipeline where the exposure and the flow velocity are greatest. The pressure sensors in comparison can be placed anywhere in the pipe, even in the recessed and sheltered areas provided at flanged access points.

The researchers decided not to perform aggressive erosion testing in the test bed due to concerns over internal damage and safety. Thus, accelerated erosion testing was performed using sandblasting equipment. Due to the high air flow (30-50 meters per second (m/s)), high density particles (100-mesh) and high nozzle pressure (30 pounds per square inch (psi)) this treatment is far more abrasive than what could realistically be expected inside a pipeline. Each test was therefore conducted over a very short period of time, 1-2 minutes, and in a distance of 15-30 centimeters (cm) from the nozzle.

An additional abrasion resistant silicon carbide (SiC) coating was deposited during fabrication of the flow sensors (Figure 31). This coating faces the on-coming particles and increases wear performance.

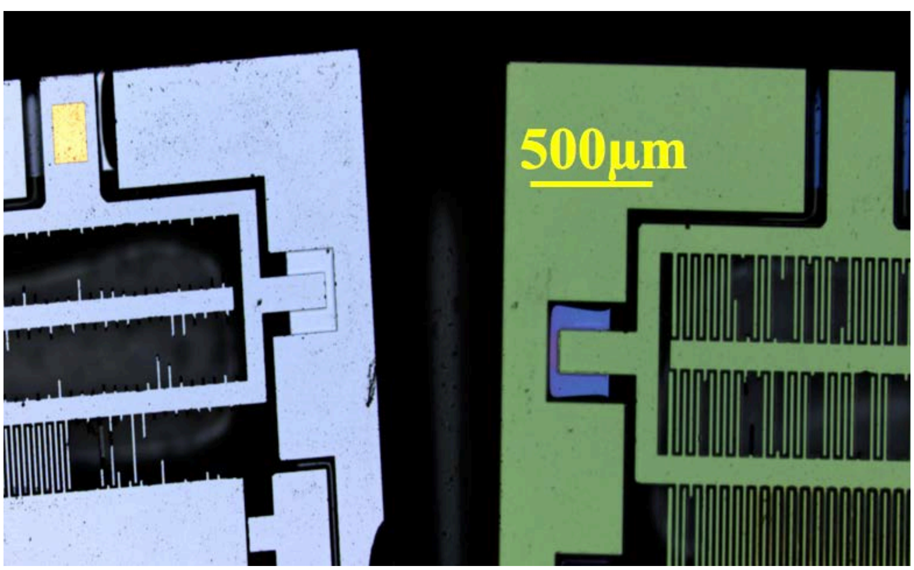
Figure 31: Devices With and Without Coating



Source: UC Berkeley

Figure 32 is a micrograph of the samples after sandblasting. The SiC coated device withstands this treatment much better than the uncoated version. In the uncoated device, most of the capacitor fingers are completely broken off, whereas a large proportion of the fingers on the coated version are still intact.

Figure 32: Capacitor Fingers After 1.5 Minutes Testing, at 30 cm from the Nozzle



Source: UC Berkeley

After an experiment at a nozzle distance of 15 cm a look at the paddle cantilevers reveals that the uncoated ones show greater wear. This is detrimental in operation as it will decrease the stiffness and thus alter the sensitivity of the sensor readout. In conclusion, the SiC coating is very effective in protecting the flow sensors against wear even in largely exaggerated, very harsh conditions.

9.2.2 Temperature Fluctuations

All flow sensors are sensitive to the variations in the density of the gas, which in turn is a function of its temperature. The benefit of the capacitive (compared to piezoresistive transduction) is its insensitivity to temperature fluctuations. To verify this, the flow sensor was tested at different airflow temperatures. These tests were conducted in the apparatus shown in Figure 33.

Figure 33: Temperature Measurement Apparatus for Flow Sensors

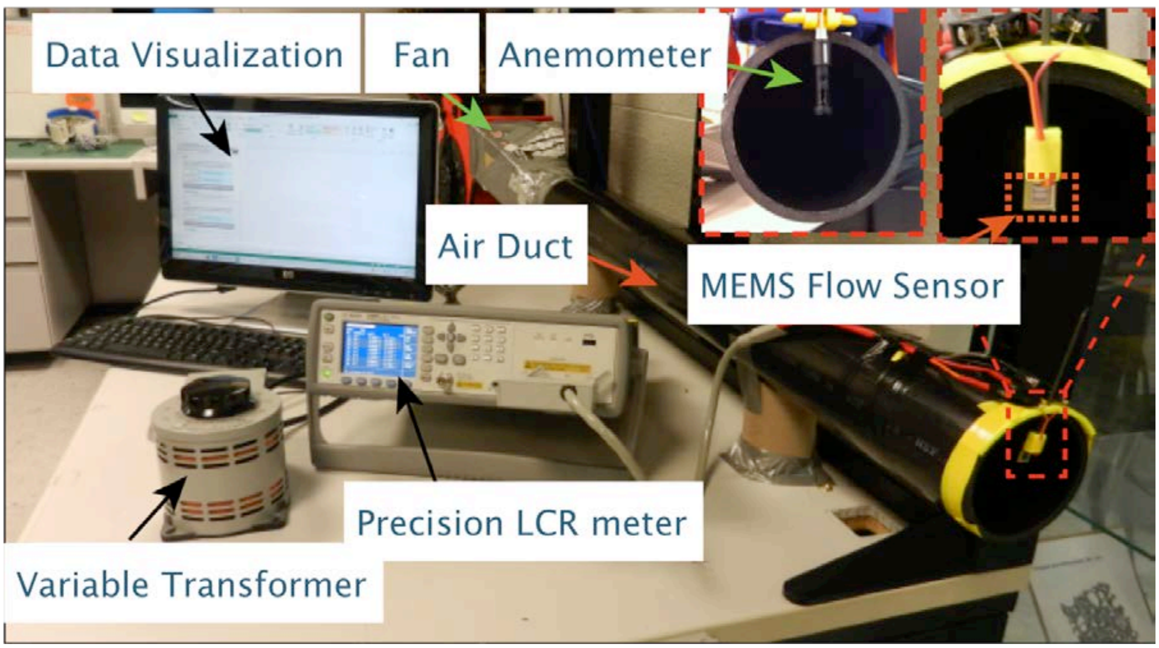
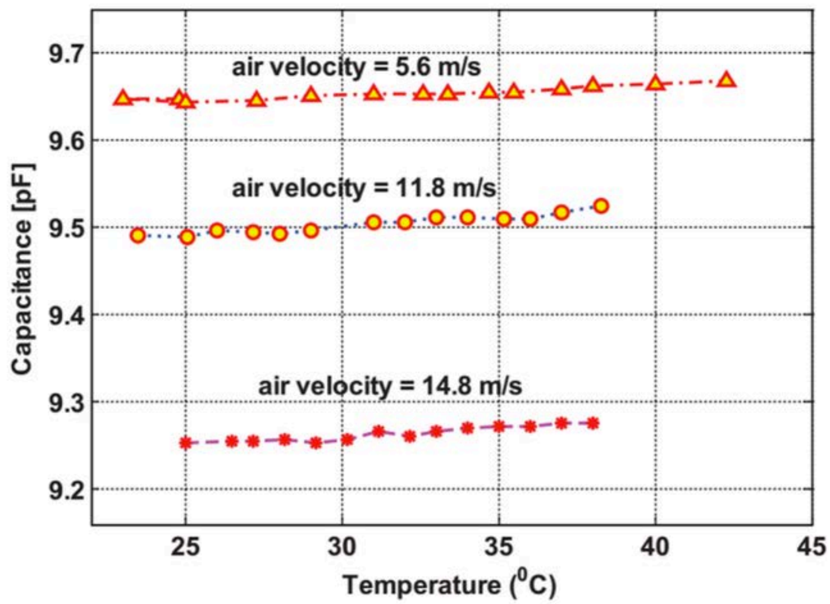


Photo Credit: UC Berkeley

A heater was placed in the duct to heat the air. The output capacitance was measured at constant velocity when increasing the temperature. The air temperature was adjusted from 23°C to 43°C for low velocity and to 37°C for high velocity. The experimental results are shown in Figure 34. The output capacitance changed very slightly when changing the temperature. In particular, the capacitance increased 0.21%, 0.34% and 0.25% for the velocity of 5.6 m/s, 11.8 m/s and 14.8 m/s, respectively.

Figure 34: Response of the Flow Sensor with Changing Temperature



Source: UC Berkeley

9.3 Low-Cost Insertion Points

The research team explored several options for the low-cost insertion of these MEMS sensors in natural gas pipelines in the field. One method of deploying these sensors is to insert them where needed in the pipeline. However, the cost of drilling or tapping a new hole into a pipeline is very expensive, primarily due to the cost of shutting down the gas. Hot tapping or drilling a hole in the pipe while the pipeline in in service, with gas flowing under pressure, is a less costly alternative. This procedure is growing more popular, especially on smaller pipes (less than 12 inches diameter); however the procedure is still fairly expensive for larger diameter pipe. The team concluded that MEMS sensors could be inserted in the pipelines via hot tapping, especially when another hot tapping point is needed to reduce the cost. Another alternative is to attach the sensors to devices going in the pipe, such as “pigs”, which are widely used to clean and inspect pipelines, or crawlers. These typically require the pipeline to be taken out of service. A relatively new inexpensive device, called the SmartBall by Pure Technologies, is a four inch or greater diameter foam sphere with sensors that can float through the pipelines. The researchers talked to the manufacturer and while the technology seems promising, concluded more research was necessary to make a determination of feasibility.

9.4 Conclusions

- The 5 millimeter by 5 millimeter dimensions of each sensor could only be reduced by a significant effort in fabrication process.
- The researchers perform aggressive erosion testing using sandblasting equipment

- The Silicon Carbide coating on the flow sensor dramatically reduced the erosion damage.
- The flow sensor was tested at temperatures ranging from 23 to 43 °C, at three different air flow rates
- The output differed by less than 0.5%, showing great stability.
- The researchers explored several options for inserting these MEMS sensors into a natural gas pipeline, such as hot tapping (inserting a test point site while the pipe is in service) and Smart Balls (foam balls with acoustic sensors that float through the pipeline). The researchers concluded that the current access points at valve sites and metering stations are appropriate for inserting the MEMS sensors.

CHAPTER 10: Conclusions

- Most typical gas pipeline diagnostic techniques are intermittent in data reporting, or require offline operation (resulting in costly service disruptions) and are too expensive for ubiquitous distribution.
- MEMS scale pressure and flow sensors would provide the greatest impact in achieving a safe, low-cost, real-time monitoring solution for natural gas pipelines.
- The team designed a sensor package with sensor, battery, and low-power radio; test results showed it accurately transmitted data.
- The research team designed a prototype pressure sensor with a diaphragm that changes capacitance with changes in pressure; the diaphragm employs touch-mode.
- The team designed a prototype flow sensor with a paddle-like cantilever attached at one end that also changes capacitance as the paddle is bent with the flow of air or gas
- Laser ultrasonic testing is a viable approach for diagnosing offline pipelines; the prototype micro ultrasonic sensors could measure flow for small diameter pipes
- A test bed was designed, fabricated, validated, and installed to test the MEMS sensors.
- After design modification, the test results of the pressure sensors showed appropriate sensitivity and accurate measure of pressure.
- While the flow sensor was successfully tested in a laboratory environment, the initial tests of the flow sensors in the test bed found that particles from the interior of the test bed disrupted the measurement.
- The results of the accelerated erosion testing showed that the Silicon Carbide coating on the flow sensor dramatically reduced the erosion damage.
- The flow sensor was tested at various temperatures; the output different by less than 0.5%, showing great stability of measurement across temperature.
- The researchers explored several options for inserting these MEMS sensors into a natural gas pipeline, and concluded that the current access points at valve sites and metering stations are appropriate for inserting the MEMS sensors.
- Initial estimations show that MEMS sensors can be fabricated for less than $18 each.
- Estimations of instrumenting a gas utility valve station with miniature flow, impact, and pressure sensors are below $70 per sensor package or node, and $500 per valve station.

Future Work

A follow-up study could investigate the operation of the developed sensors in at higher pressures (200-1,350 psi) and using methane instead of air. However, for safety reasons, these experiments would have to be performed off campus in an open air environment and would thus require relocation of the test bed and necessary equipment. The issues with conductive particles in the flow that are disturbing the readout of the flow sensors are another area of future research. The next step with the pressure sensors is to integrate them into a complete sensor package with the communication as it was presented earlier in this report. The technology may be licensed to an external company in order to make the progression from research result to commercial product for utilities companies to use. Lastly, the test bed is now available for future projects; there are several additional access ports that enable expansion and integration of different sensors, cameras, light sources, etc. Investigation of non-insertion based technologies, such as particle image velocimetry, ultrasonic flow measurements and external strain gauges are particularly interesting to the researchers.

GLOSSARY

Term	Definition
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
capacitor	A capacitor is a passive two-terminal electrical component used to store energy electrostatically in an electric field; capacitance is the ability of a body to store an electrical charge.
DC	Direct Current
DPI	Dye Penetration Inspection
EPIC	Electric Program Investment Charge
Farad	A Farad is the SI derived unit of electrical capacitance, the ability of a body to store an electrical charge.
FEM	Finite Element Modeling
flow	The movement of the gas or air through the pipeline
Hydrostatic Testing	Testing of sections of a pipeline by filling the line with water and pressurizing it until the nominal hoop stresses in the pipe reach a specified value.
LUT	Laser Ultrasonic Testing is a non-destructive ultrasonic measurement technique used to measure pipe thickness and defects in pipe surfaces
MAOP	Maximum Allowable Operating Pressure
MEMS	Micro-electro-mechanical systems are small (usually measured in millimeters) devices made through microfabrication techniques, such as pressure sensors found in car tires
MPI	Magnetic Particle Inspection
nondestructive (testing, analysis or method)	Nondestructive means the ability to evaluate the properties of a material, component or system without causing damage.
Off-Line	A pipeline section that is removed from service.
On-Line	A pipeline section that is in service.

pig	A generic term signifying any independent, self-contained device, tool, or vehicle that moves through the interior of the pipeline for inspecting, dimensioning, or cleaning. (The original devices made a squealing sound when moving through the pipes, hence the name)
pMUT	piezoelectric Microfabricated Ultrasonic Transducers, ultrasonic sending and receiving transducers, may be adapted for use inside natural gas pipelines to measure gas flow velocity.
Pressure	Level of force per unit area exerted on the inside of a pipe or vessel.
psi	pounds per square inch
Real-time	Data transfer occurs entirely within the span of and at the same rate as the actual event.
Smart Grid	Smart Grid is the thoughtful integration of intelligent technologies and innovative services that produce a more efficient, sustainable, economic, and secure electrical supply for California communities.
UC Berkeley	University of California, Berkeley

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APPENDICES

Appendix A: Benchmarking Existing Diagnostic Approaches for Natural Gas Pipelines

Appendix B: Micro-Electro-Mechanical Systems Sensor Designs for Natural Gas Pipelines

Appendix C: Workshop Notice

Appendix D: Workshop Notice

Appendix E: Laboratory Testing Of Low-Cost Sensors for Natural Gas Pipelines

Appendix F: Sensors Test Bed Design and Validation

Appendix G: Sensor Testing In the Test Bed

Appendix H: Data Analysis of Sensor Testing

Appendix I: Miniaturization and Lifetime Testing Of Sensors

Appendix J: Workshop

These appendices are available as a separate volume, publication number CEC-500-2014-104-AP.